Title: Quarkonium: experimental overview

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Intended for: Hard Probes 2020, 2020-06-01 (Austin, Texas, United States)

Issued: 2020-06-04

Quarkonium: experimental overview

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10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

31 May 2020 to 5 June 2020
The University of Texas at Austin

Outline

- Introduction

- $Q\bar{Q}$ in Small Systems → Large Systems
  - Focus on medium interactions

- Exotic hadrons containing $Q\bar{Q}$
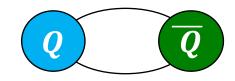 - X(3872) in the QCD medium

- Brief look to the future

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  - X(3872) in the QCD medium

- Brief look to the future
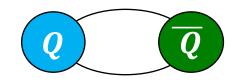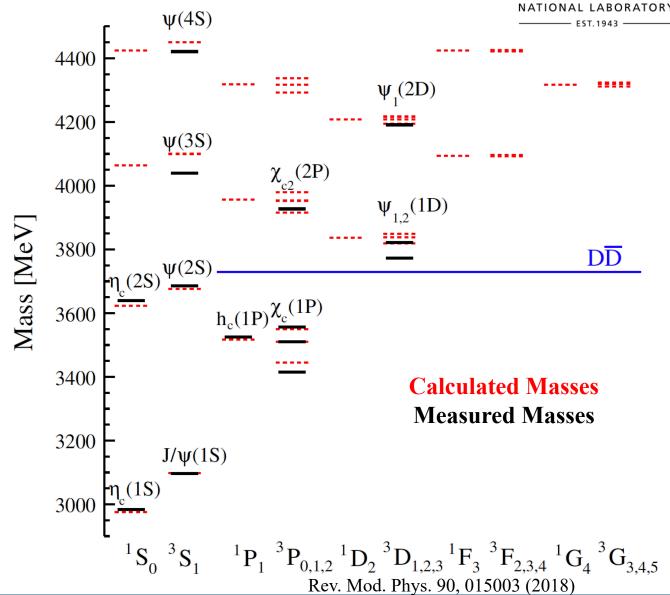
Heavy $Q\bar{Q}$ states in vacuum
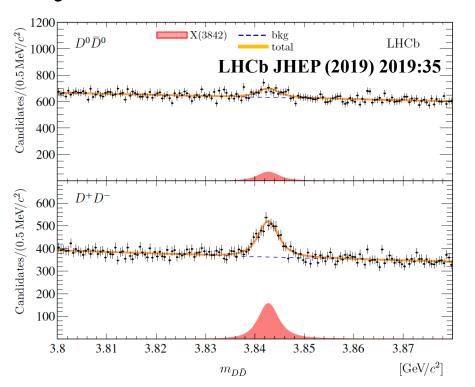

Solve Schrodinger equation with the potential

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

Phys. Rev. D 72, 054026 (2005)

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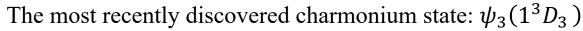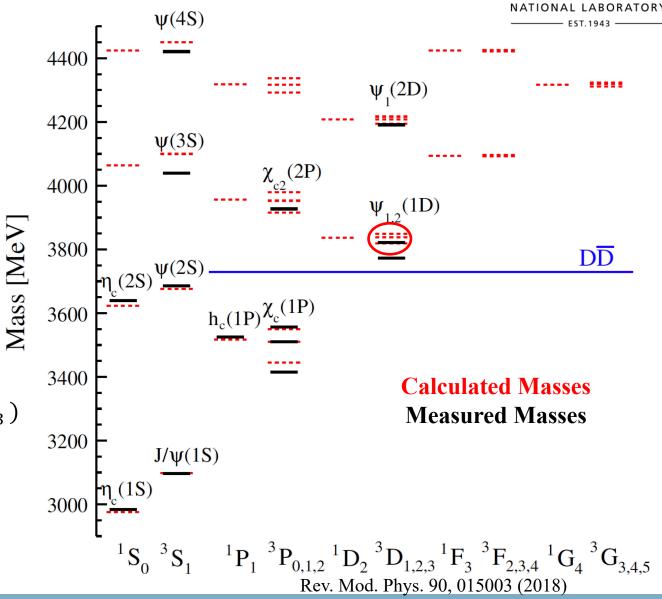
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Calculated Masses
Measured Masses

Rev. Mod. Phys. 90, 015003 (2018)

Heavy $Q\bar{Q}$ states in vacuum

The most recently discovered charmonium state: $\psi_3(1^3D_3)$

Measured mass: $3842.71 \pm 0.16 \pm 0.12$ MeV
Predicted mass: 3849 MeV

Incredibly rich structure, accessible theoretically and experimentally

Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium

Increasing T, N_{ch}

Dense medium

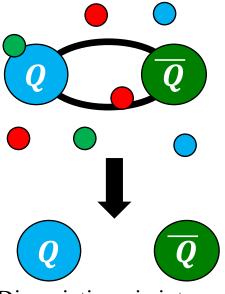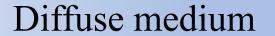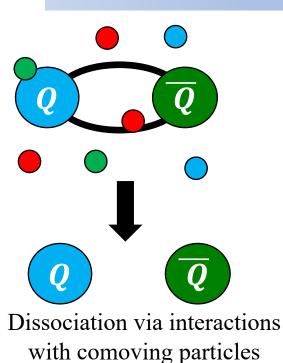Dissociation via interactions
with comoving particles
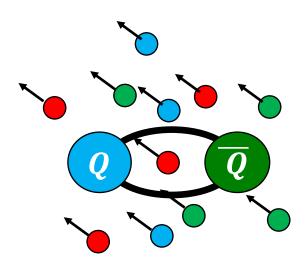
Heavy $Q\bar{Q}$ states in the QCD medium

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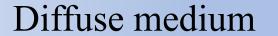
Dense medium

Dissociation via interactions with comoving particles
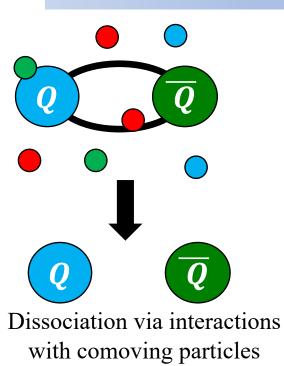
Hydrodynamic flow induced by pressure gradients (initial state?)

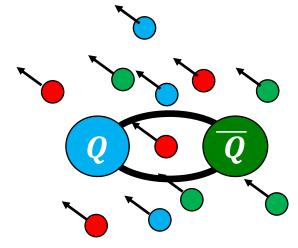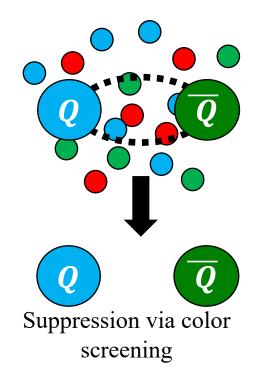# Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium — Increasing T, N$_{ch}$ — Dense medium
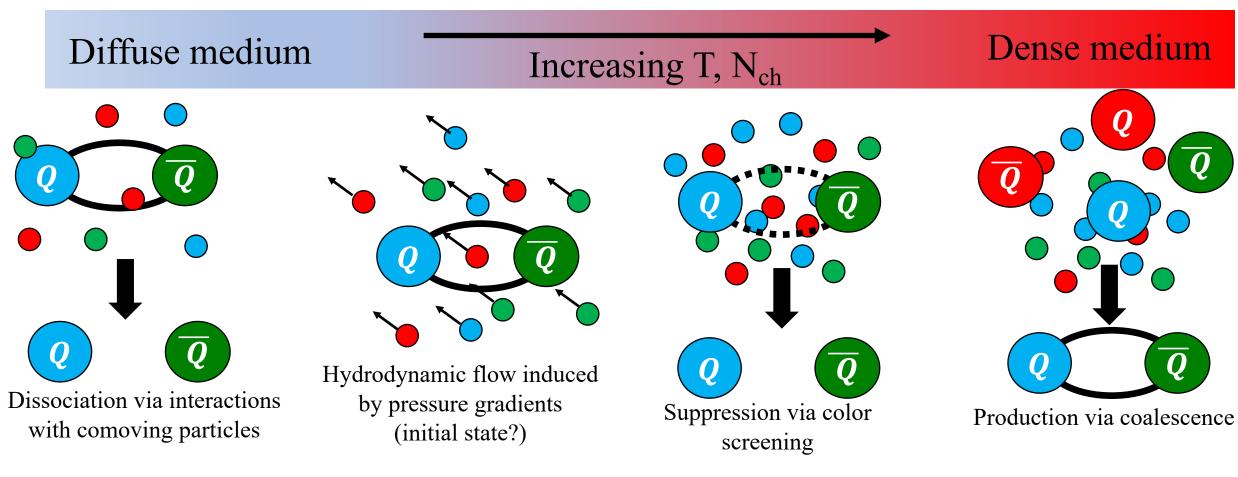
Dissociation via interactions with comoving particles

Hydrodynamic flow induced by pressure gradients (initial state?)

Suppression via color screening

Heavy $Q\bar{Q}$ states in the QCD medium

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Production via coalescence

Heavy $Q\bar{Q}$ states in the QCD medium

Diffuse medium

Increasing T, N_{ch}

Dense medium

Dissociation via interactions with comoving particles

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Production via coalescence

*Additional initial state effects from modified nPDF and energy loss can also be significant in collisions with nuclei.

Experimentally, we use different collision systems/kinematic regions to prepare environments where different effects dominate for different probes.

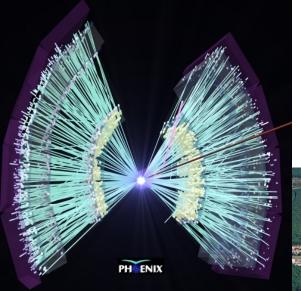# Every experiment contributes to quarkonia physics
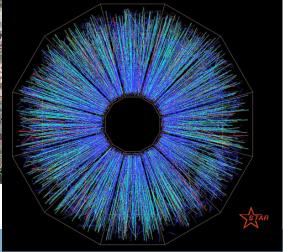
Taken together:

-5 < y < 5

$0 < p_T <$ several hundred GeV

~0 < T < hundreds of MeV

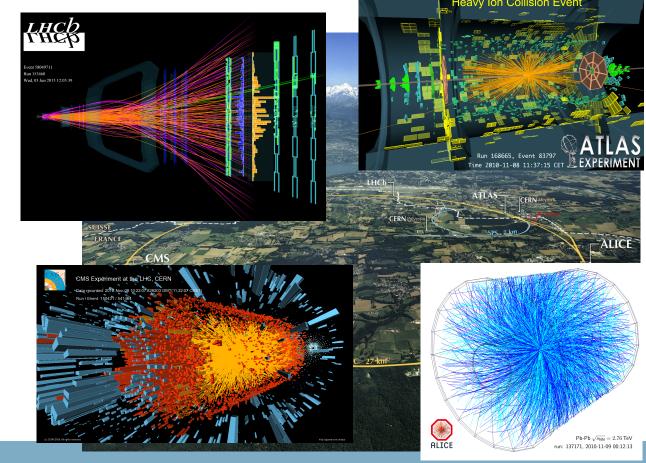# Outline

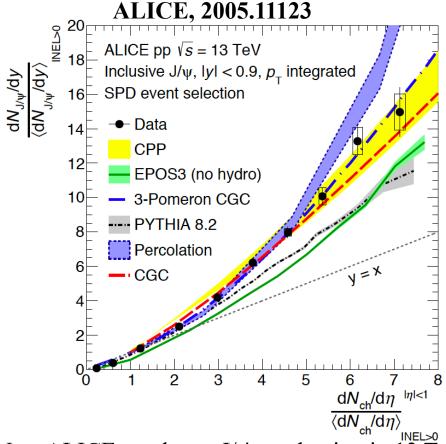- Introduction

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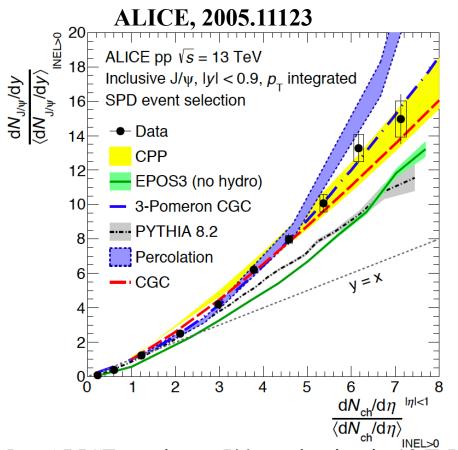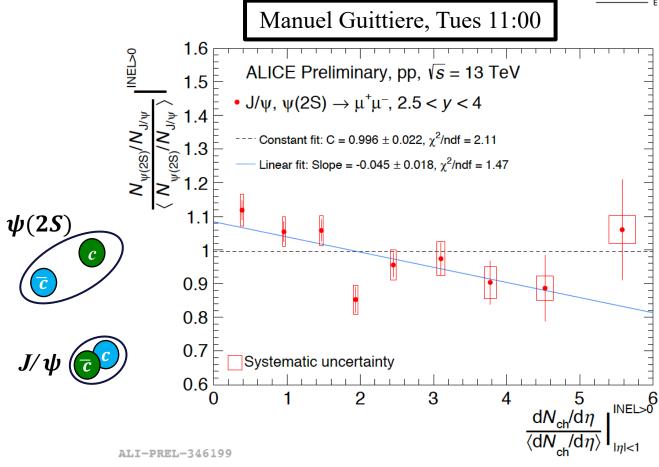
Charmonium in *pp* vs. multiplicity

ALICE, 2005.11123

New ALICE results on J/ψ production in 13 TeV pp shows faster-than-linear growth with multiplicity: various CGC calculations match data
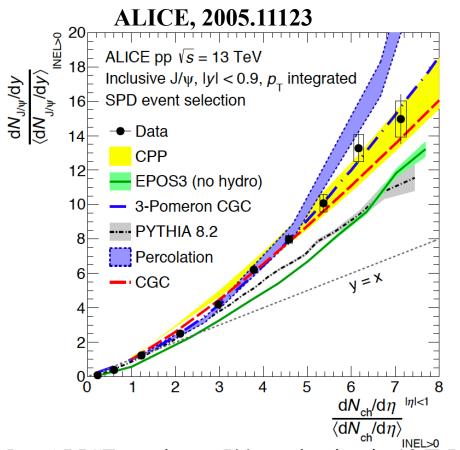
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Manuel Guittiere, Tues 11:00

ALI-PREL-346199

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Hints that ψ(2S) production does now grow as fast as J/ψ with multiplicity – initial state models should give similar trend for both. Final state effect suppressing ψ(2S) in *pp*?

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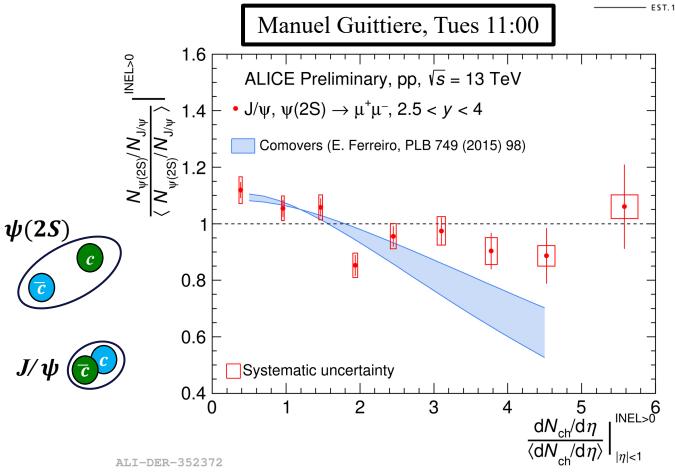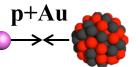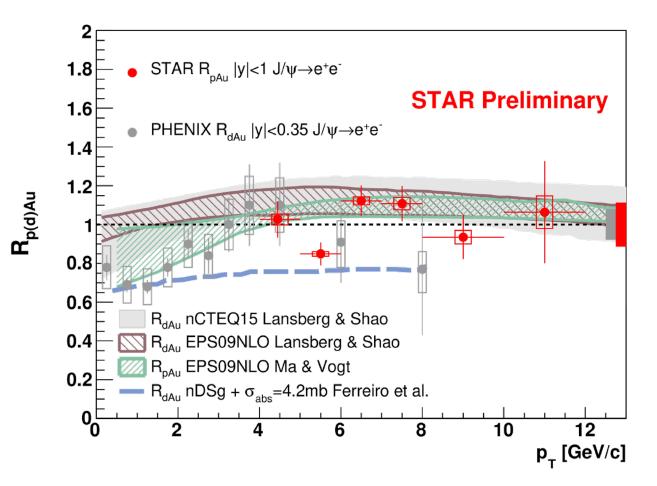
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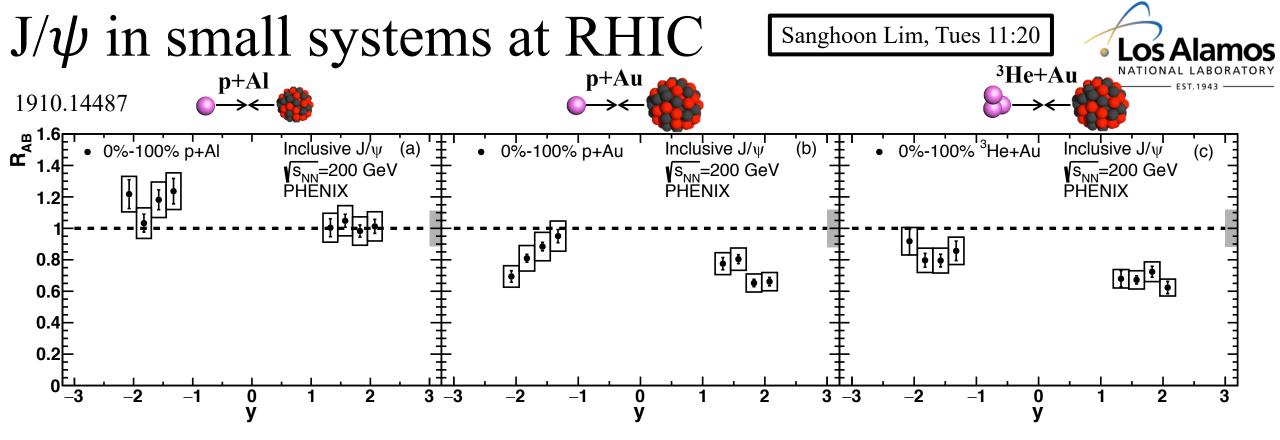
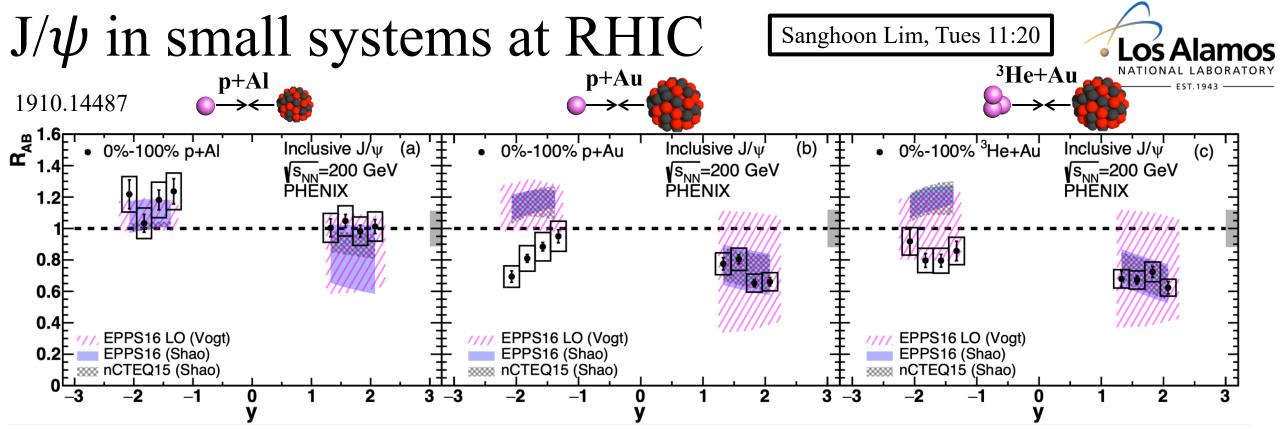# J/ψ in small systems at RHIC

p+Au

Midrapidity STAR data shows little J/ψ modification at intermediate p_T:
- Consistent with nPDF calculations
- Consistent with PHENIX d+Au data
- CNM not dominant effect in AA in this range

J/ψ in small systems at RHIC

J/ψ in small systems at RHIC

Los Alamos
NATIONAL LABORATORY
— EST.1943 —
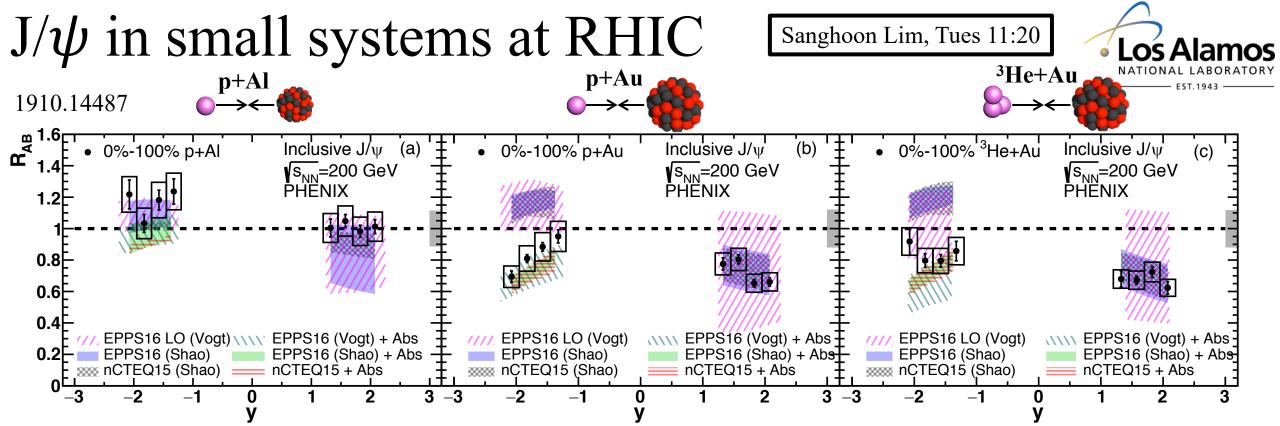
1910.14487

p+Al

p+Au

³He+Au

Forward rapidity (p or 3He-going direction):
- Data generally in agreement with nPDF calculations

Backward rapidity (A-going direction):
- Data from Au nucleus is **inconsistent with nPDF calculation**:
  - Additional effects *required* to explain data

Significantly improved precision in state-of-the art nPDF calculations, which include D, J/ψ, and Υ(1S) LHC data
Kusina, Lansberg, Schienbein, Shao,
Phys. Rev. Lett. 121, 052004 (2018)

J/ψ in small systems at RHIC

LOS ALAMOS NATIONAL LABORATORY — EST. 1943

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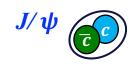Backward rapidity (A-going direction):

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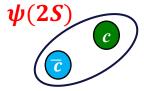 - Additional effects required to explain data

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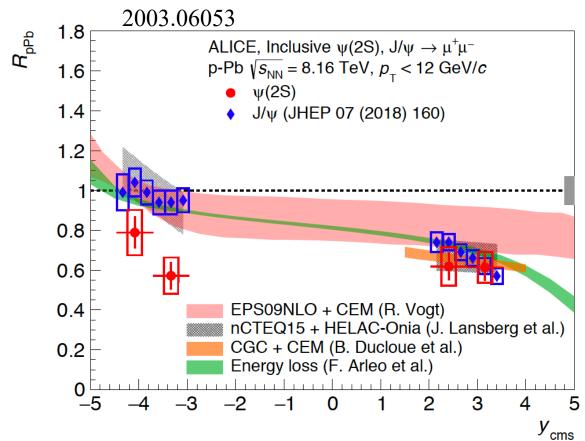Kusina, Lansberg, Schienbein, Shao,
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$Q\bar{Q}$ in pPb

J/ψ

$\psi(2S)$

At both forward and backward rapidity, J/ψ well described by nPDF calculations: initial state dominates
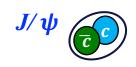
- **Marked difference from PHENIX data, where additional effects are required to match backwards J/ψ data**
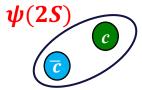- J/ψ breakup smaller at LHC - smaller crossing time
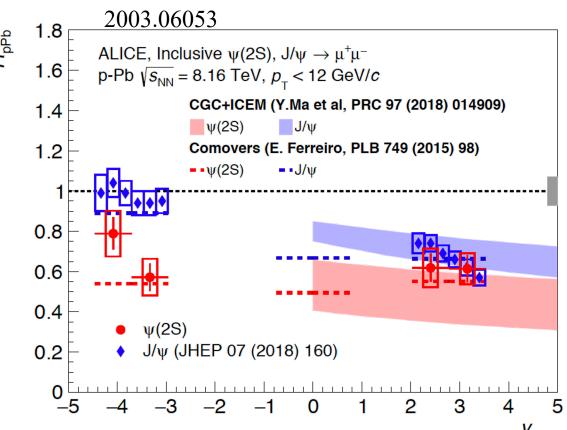
Backwards $\psi(2S)$ data shows inconsistency with nPDF

Florian Damas, Mon 1:35

$Q\bar{Q}$ in pPb

J/ψ

$\psi(2S)$

2003.06053

ALICE, Inclusive $\psi(2S)$, $J/\psi \to \mu^+\mu^-$
p-Pb $\sqrt{s_{NN}} = 8.16$ TeV, $p_T < 12$ GeV/c

CGC+ICEM (Y.Ma et al, PRC 97 (2018) 014909)
$\psi(2S)$ J/ψ
Comovers (E. Ferreiro, PLB 749 (2015) 98)
$\psi(2S)$ J/ψ

● $\psi(2S)$
◆ J/ψ (JHEP 07 (2018) 160)

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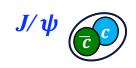- J/ψ breakup smaller at LHC - smaller crossing time

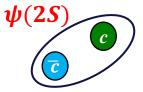Backwards $\psi(2S)$ data shows inconsistency with nPDF

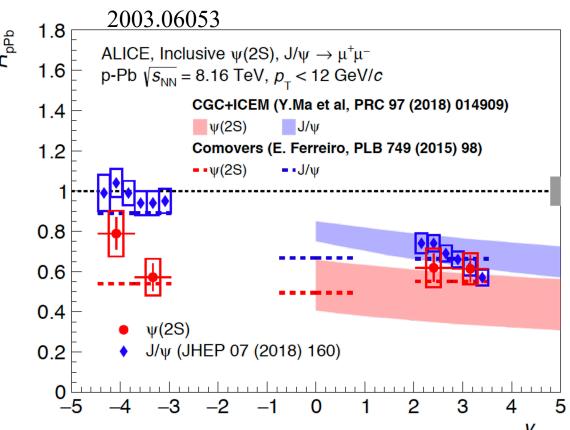- **Tension eases when final state comover breakup is included, small effect for forward.**

Similar effects previously observed by PHENIX, ALICE, LHCb
Similar sequential suppression of Υ(nS) also observed in pPb

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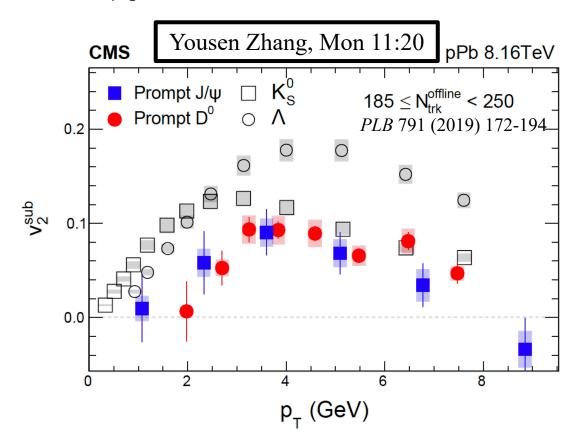- J/ψ breakup smaller at LHC - smaller crossing time

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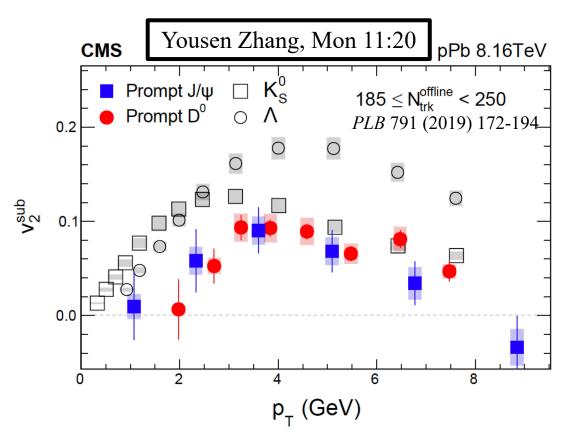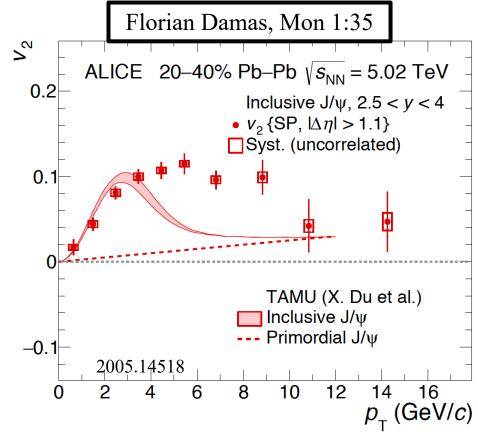Similar sequential suppression of Υ(nS) also observed in pPb

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J/ψ flow

Data on J/ψ production is consistent with nPDF, however: Significant J/ψ v_2 observed in pPb collisions

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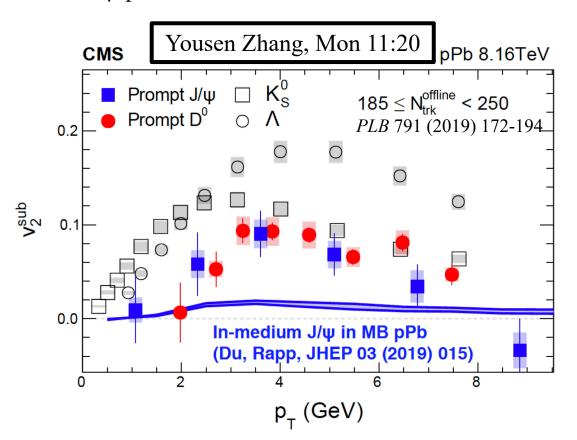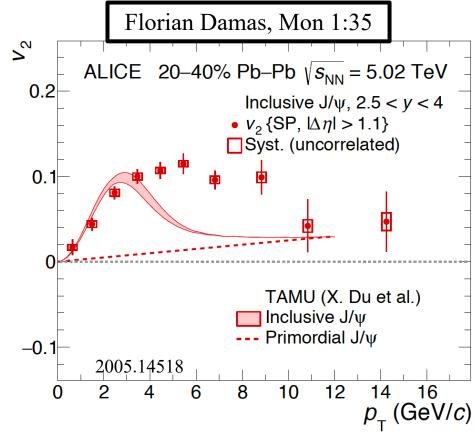

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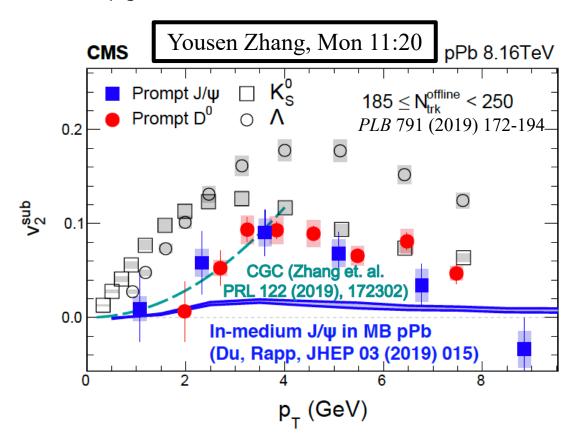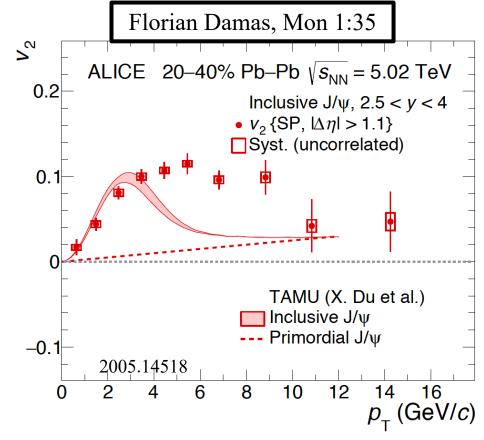

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- **Transport model with short lived plasma phase in pPb does not give large v2 in pPb** (does describe low pT PbPb)

J/ψ flow

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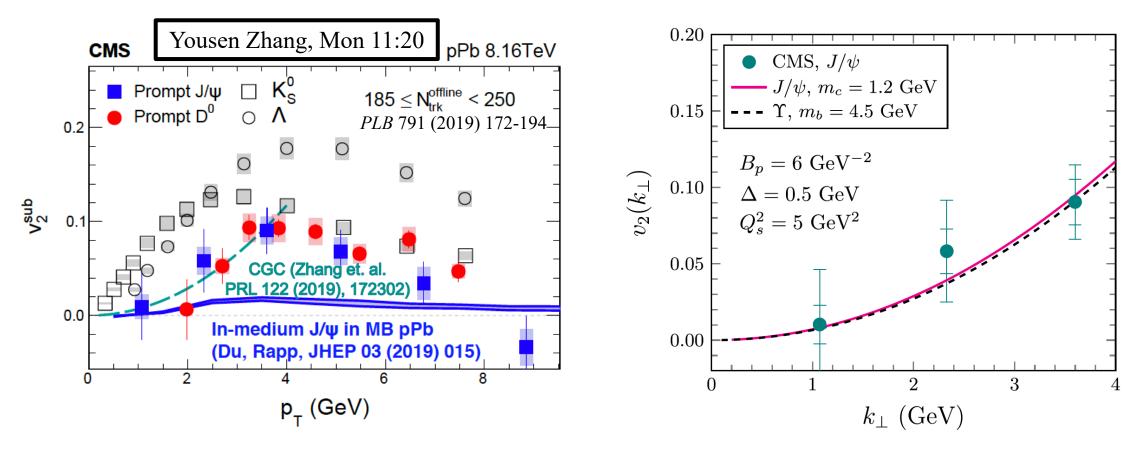

- Similar to PbPb; some differences observed at high pt, typically attributed to L dependent energy loss, not present in pPb
- **Transport model with short lived plasma phase in pPb does not give large v2 in pPb** **(does describe low pT PbPb)**
- **CGC calculation describes part of pPb v2; however CGC has mixed results describing light sector v2**
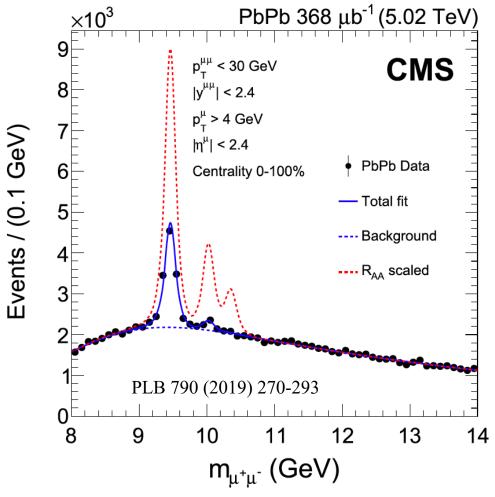
MAJOR OPEN QUESTION

J/ψ flow

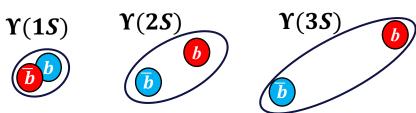Data on J/ψ production is consistent with nPDF, however: Significant J/ψ v_2 observed in pPb collisions

- **CGC calculation gives very similar v2 for Upsilon states on pPb: next challenge for experiments**
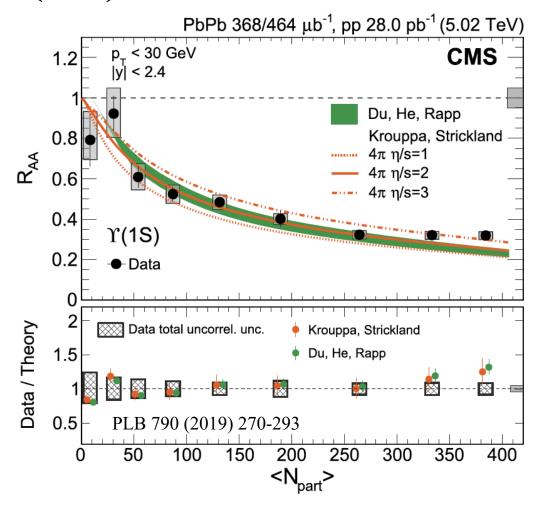
Υ(nS) in PbPb

PLB 790 (2019) 270-293

Textbook example of color screening

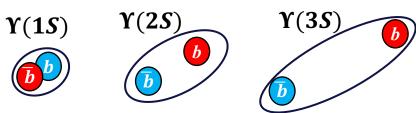$\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$

- Three well defined state observable in $\mu^+\mu^-$
- Bottom density relatively low – expect minimal effects from recombination
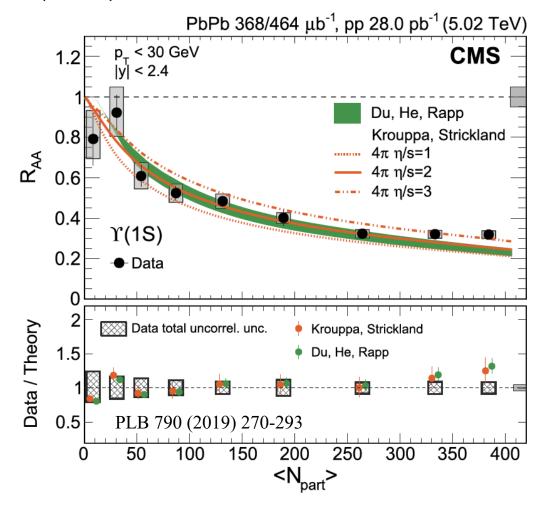
Υ(nS) in PbPb

PbPb 368/464 μb^{-1}, pp 28.0 pb^{-1} (5.02 TeV)

$p_T < 30$ GeV
$|y| < 2.4$

CMS

R_{AA}

Du, He, Rapp
Krouppa, Strickland
4π η/s=1
4π η/s=2
4π η/s=3

Υ(1S)
Data

Data / Theory

Data total uncorrel. unc.
Krouppa, Strickland
Du, He, Rapp

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<N_{part}>

Textbook example of color screening
Well described by models

$\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$

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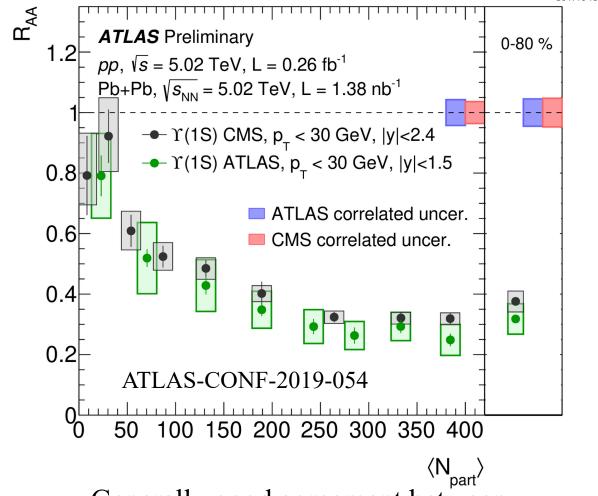- Bottom density relatively low – expect minimal effects from recombination

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Los Alamos
NATIONAL LABORATORY
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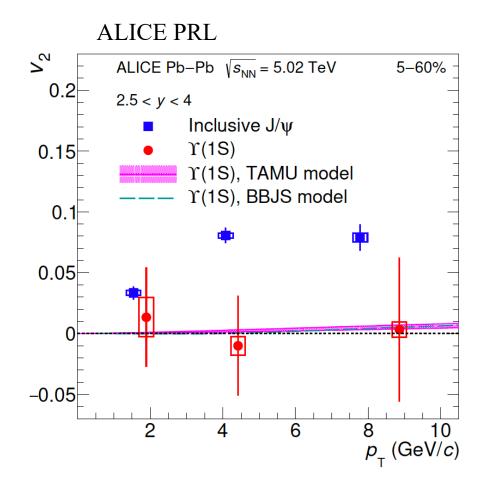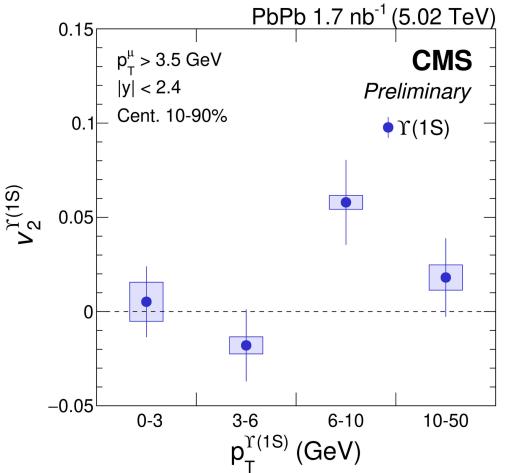

Textbook example of color screening
Well described by models

Generally good agreement between
ATLAS and CMS

$Q\bar{Q}$ flow in PbPb

In contrast to J/ψ, no significant v$_2$ is observed for Υ(1S) by ALICE or CMS.
Little or no recombination due to relative low b density in QGP, as expected from models.

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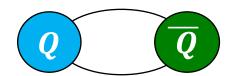- Exotic hadrons containing $Q\bar{Q}$
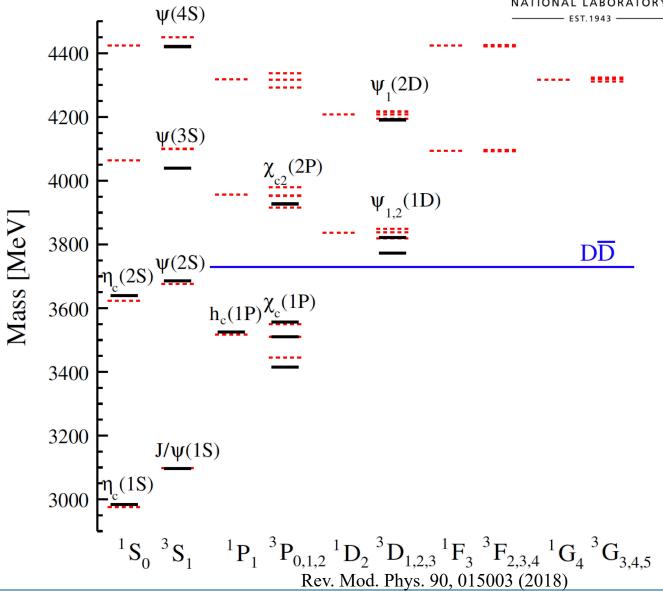 - X(3872) in the QCD medium

- Brief look to the future

**Hard Probes 1-9: 0 talks
devoted to X(3872)**

**Hard Probes 10: 4 talks!
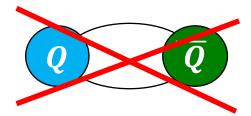2 experiment, 2 theory**
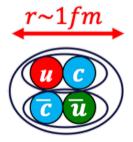
Exotic $Q\bar{Q}$ states: XYZ
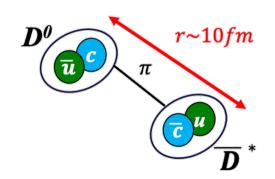
Exotic $Q\bar{Q}$ states: XYZ

Dozens of states containing $c\bar{c}$ and $b\bar{b}$ have been discovered that are not predicted by any $Q\bar{Q}$ potential model

Compact tetraquark

$r \sim 1fm$

Hadronic molecule

$r \sim 10fm$

Thousands of theory papers exploring possible structures, but no consensus on even the first exotic, X(3872)

Primarily measured as products of b decays in vacuum

Rev. Mod. Phys. 90, 015003 (2018)

Exotic $Q\bar{Q}$ states: XYZ

Dozens of states containing $c\bar{c}$ and $b\bar{b}$ have been discovered that are not predicted by any $Q\bar{Q}$ potential model
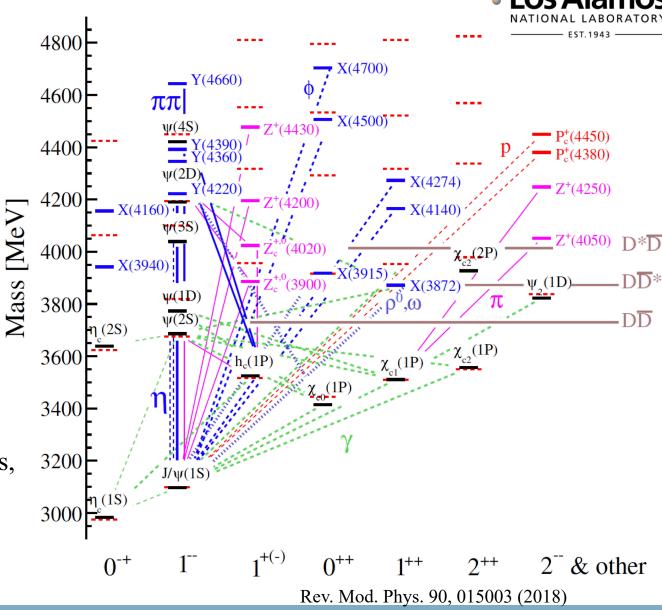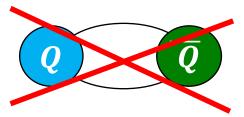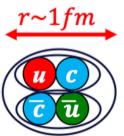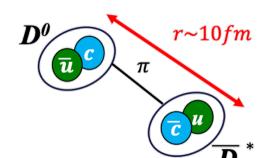
Compact tetraquark

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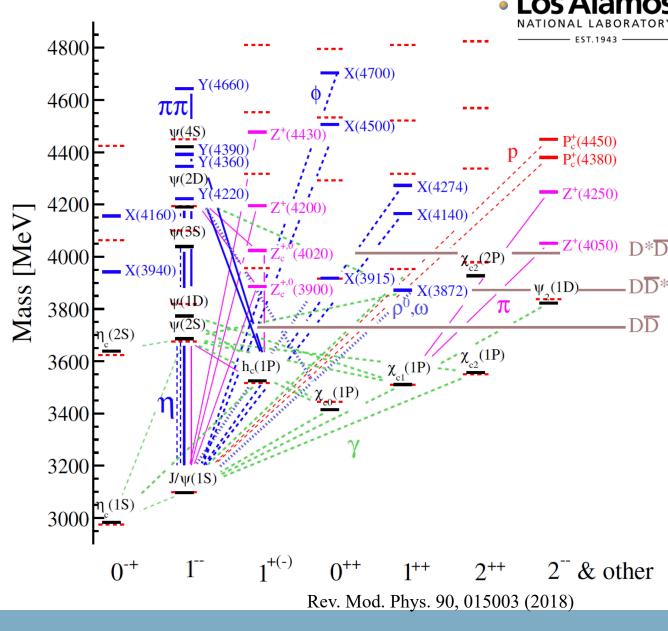**Hadronic molecule**

D^0 $r\sim 10fm$

$\bar{D}^*$

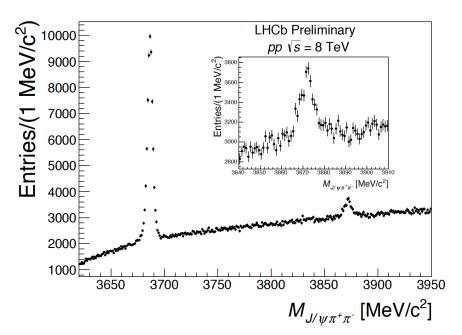Interactions in QCD medium are dependent on binding energy/structure

$\Updownarrow$

Production of multiquark exotics is especially sensitive to recombination/coalescence effects that are expected in heavy ion collisions
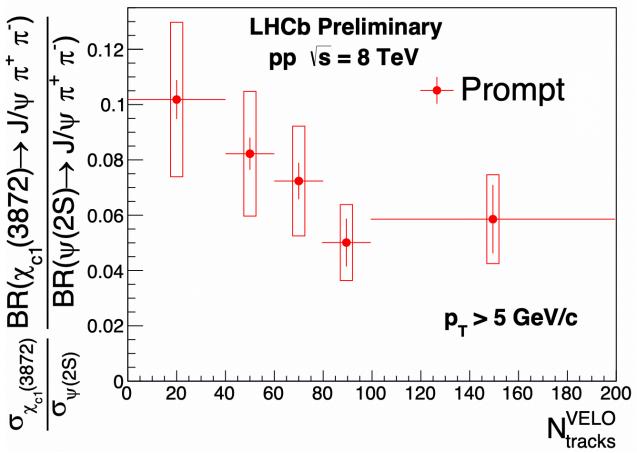
Rev. Mod. Phys. 90, 015003 (2018)

Exotic X(3872) in diffuse medium (8 TeV *pp*)

LHCb-CONF-2019-005

- Prompt X(3872)/ ψ(2S) decreases with activity
  - X(3872) suppressed more than ψ(2S)

Cameron Dean, Wed 12:25

Systematic uncertainty box fully
correlated point-to-point

Exotic X(3872) in diffuse medium (8 TeV pp)

LHCb-CONF-2019-005

- Prompt X(3872)/ ψ(2S) decreases with activity
  - X(3872) suppressed more than ψ(2S)
- *B*-decay component consistent with constant
  - Production in vacuum unaffected

Cameron Dean, Wed 12:25
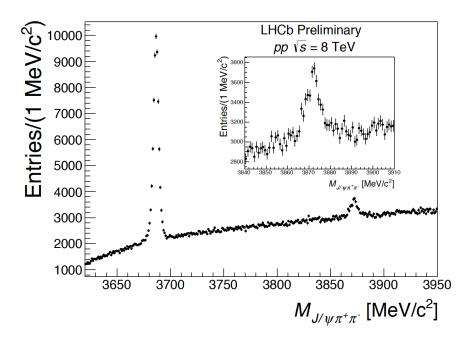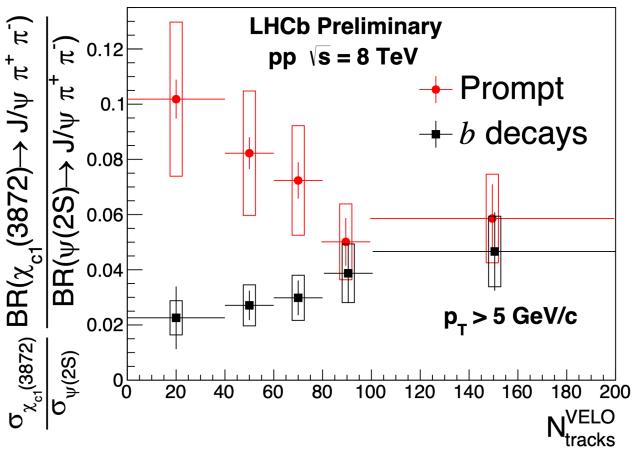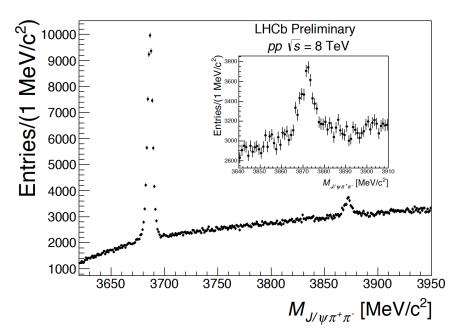
Systematic uncertainty box fully correlated point-to-point

Exotic X(3872) in diffuse medium (8 TeV *pp*)

LHCb-CONF-2019-005

$$\sigma^{\mathrm{co}-\mathcal{Q}}(E^{\mathrm{co}}) = \sigma^{\mathcal{Q}}_{\mathrm{geo}} \times \left(1 - \frac{E^{\mathcal{Q}}_{\mathrm{thr}}}{E^{\mathrm{co}}}\right)^n$$

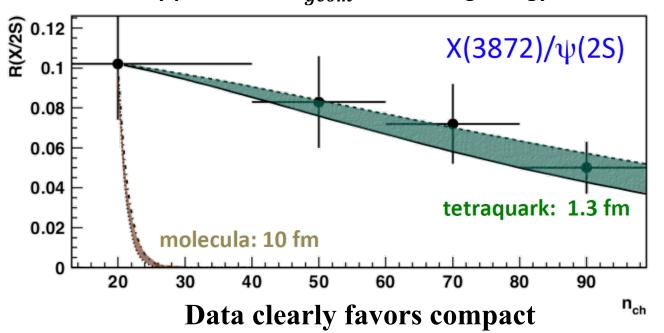**Directly probes size σ_{geom} and binding energy**

- Prompt X(3872)/ ψ(2S) decreases with activity
  - X(3872) suppressed more than ψ(2S)
- *B*-decay component consistent with constant
  - Production in vacuum unaffected
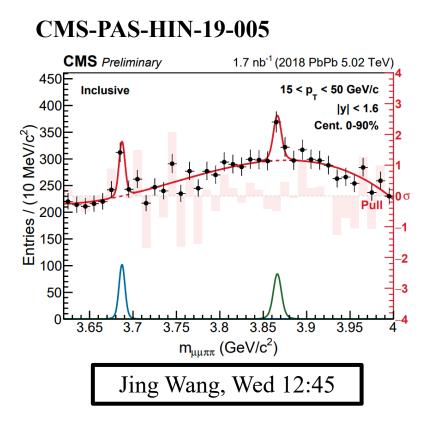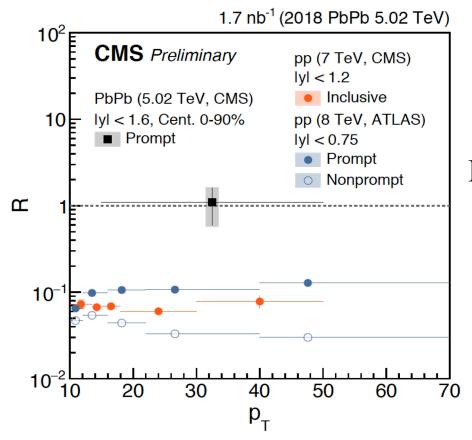
Data clearly favors compact tetraquark interpretation

Cameron Dean, Wed 12:25

Elena Ferreiro, Wed 1:05

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005

Jing Wang, Wed 12:45

Recombination of X(3872)
at pT > 15 GeV?

Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005

Biaogang Wu, Wed 1:25

Jing Wang, Wed 12:45

Transport model gives larger yield for compact tetraquark vs. molecule by factor of ~2 in PbPb

Will be tested with future PbPb data sets.
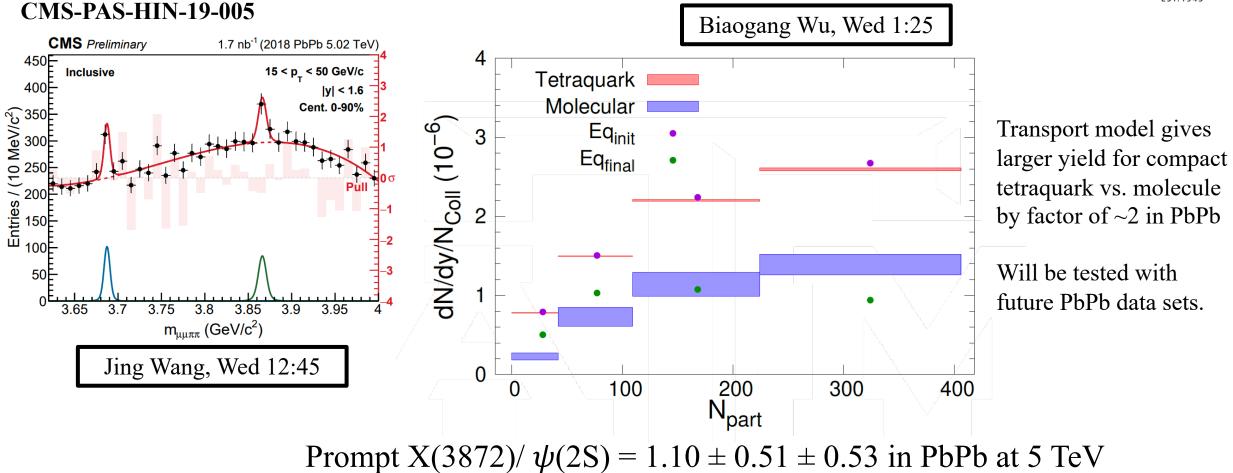
Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

Intriguing data! Inconclusive with these uncertainties.

Outline

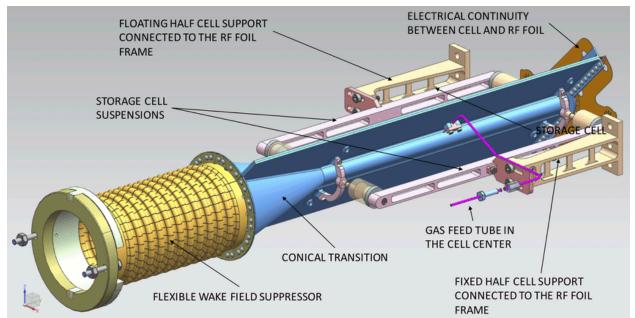- Introduction

- $Q\bar{Q}$ in Small Systems → Large Systems
  - Focus on medium interactions

- Exotic hadrons containing $Q\bar{Q}$
  - X(3872) in the QCD medium

- **Brief look to the future**

Fixed target at LHCb: SMOG II

Barbara Trzeciak (AFTER physics program), Wed 1:55

Samuel Belin (Future of LHCb), Thurs 10:55

FLOATING HALF CELL SUPPORT CONNECTED TO THE RF FOIL FRAME

ELECTRICAL CONTINUITY BETWEEN CELL AND RF FOIL

STORAGE CELL SUSPENSIONS

STORAGE CELL

GAS FEED TUBE IN THE CELL CENTER

CONICAL TRANSITION

FLEXIBLE WAKE FIELD SUPPRESSOR

FIXED HALF CELL SUPPORT CONNECTED TO THE RF FOIL FRAME

https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

Upgraded SMOG system at LHCb allows greatly increased rates of beam+injected gas collisions

No centrality limitations in p+gas or Pb+gas at LHCb

Example SMOG2 pAr at 115 GeV for one year

Int. Lumi.		80 pb^{-1}
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k
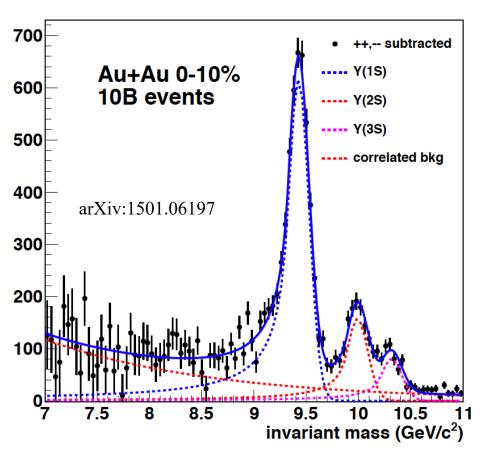
Large heavy flavor samples
Access to exotic states near RHIC energies

New detector at RHIC: sPHENIX
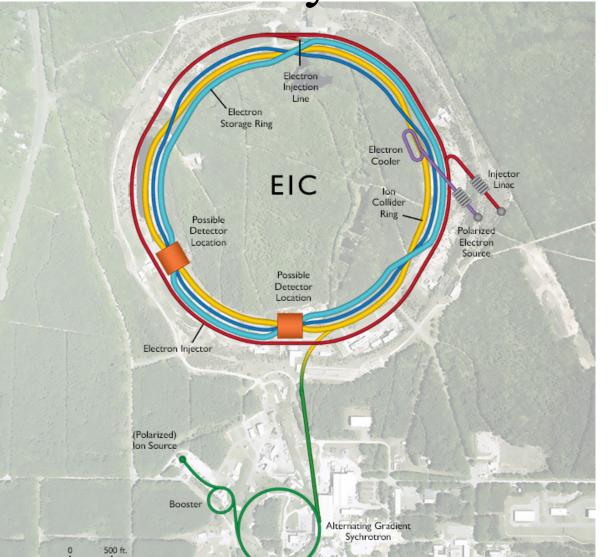
Future facility: electron-ion collider
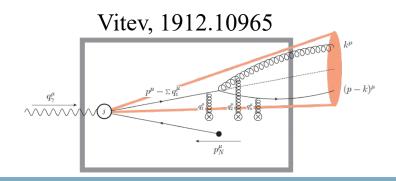

EIC site selection at BNL announced Jan 2020

Charm production inside the nucleus probes:
- Parton structure of nucleons
- nPDF modifications
- QCD energy loss

Xuan Li, Thurs 10:35

In the kinematic range accessed by the EIC, hadronization *inside the nucleus* becomes an important effect on observables

Vitev, 1912.10965

E. Aschenauer, Wed 9:15

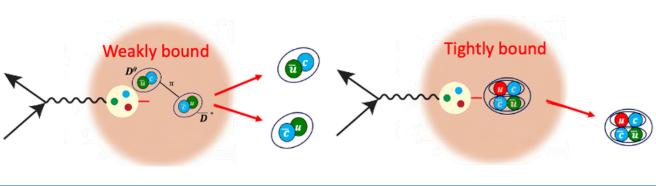# Future facility: electron-ion collider

EIC site selection at BNL announced Jan 2020

Charm production inside the nucleus probes:
- Parton structure of nucleons
- nPDF modifications
- QCD energy loss

Xuan Li, Thurs 10:35

e+A collisions have relatively low backgrounds – well suited for studies of higher charmonia and exotics: $P_c^+, Z_c^+, \chi_c, ...$

E. Aschenauer, Wed 9:15

Summary

- Quarkonia remains a major focus of heavy ion physics 34 years after Matsui and Satz
  - Contributions from all experimental collaborations – a wealth of data
  - Strong synergy with theory community

- The lines between small and large systems are continually becoming blurred
  - Final state suppression manifests in many systems at high multiplicity
  - Universal understanding of J/ψ flow from small to large systems remains elusive

- Exotic multiquark states are becoming accessible in a QCD medium
  - Medium probes exotic properties ⇔ Exotics probe medium properties

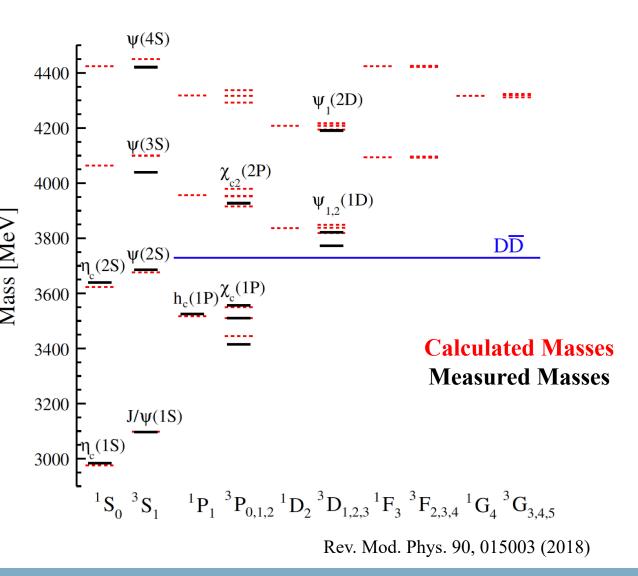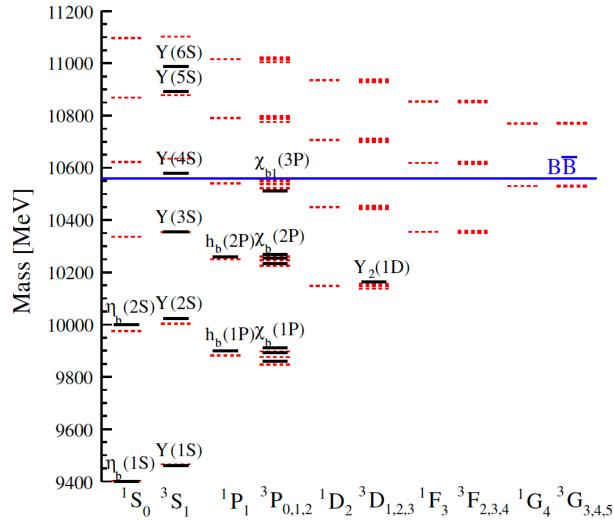- Exciting future programs of in-medium quarkonia studies at LHC/RHIC/EIC to come

BACKUPS

We have only measured 2 charmonium states in heavy ion collisions at LHC.

We have only measured 3 bottomonium states in heavy ion collisions at LHC.

Calculated Masses
Measured Masses

Rev. Mod. Phys. 90, 015003 (2018)

Quark Model of Hadrons

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

AN SU$_3$ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
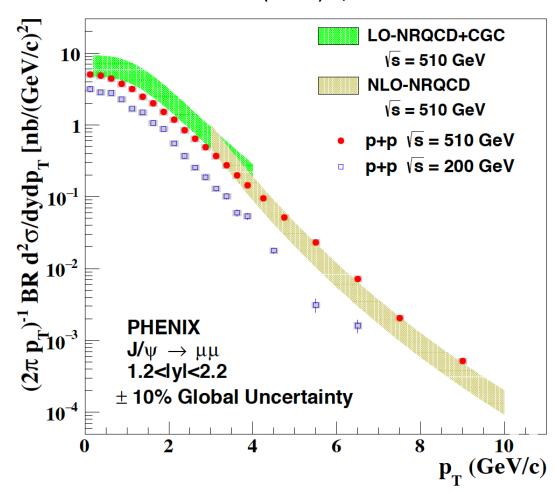
G. Zweig *)

CERN — Geneva

8182/TH.401
17 January 1964

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$, etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".
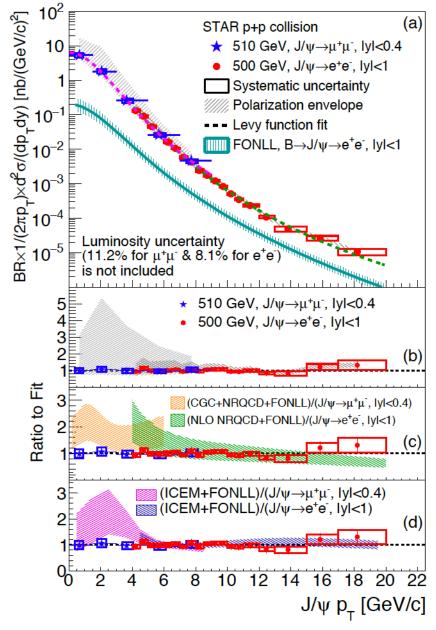
States with >3 quarks have been expected since the beginning of the quark model

Charmonium in *pp* - RHIC

PHENIX: PRD 101 (2020) 5, 052006

STAR, *PRD* 100 (2019) 5, 052009

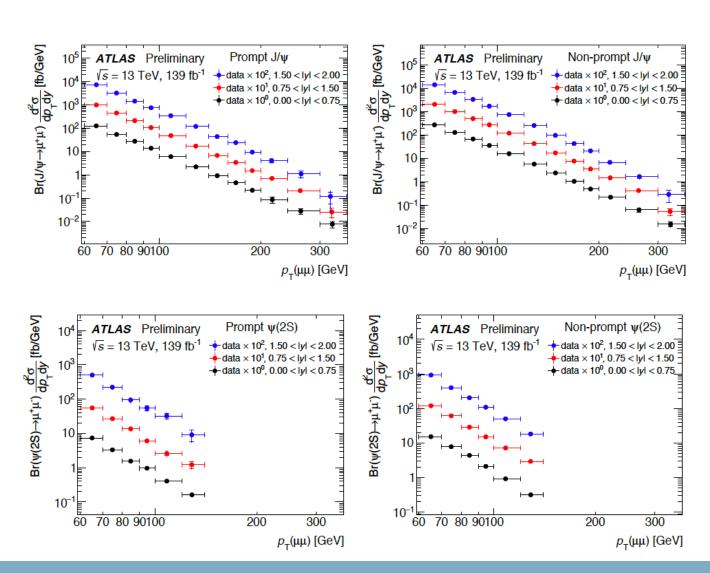Agreement with calculations across entire p_T range

Charmonium in pp - LHC

ATLAS-CONF-2019-047

Preliminary result from ATLAS:

J/ψ measured up to 360 GeV
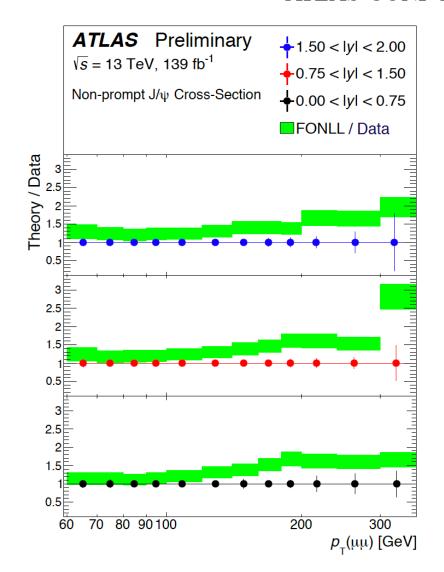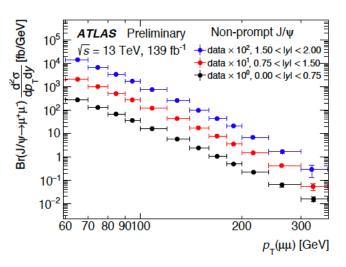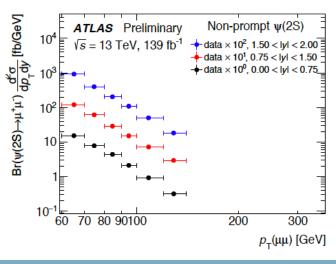ψ(2S) measured up to 140 GeV

Charmonium in pp - LHC

Preliminary result from ATLAS:

J/ψ measured up to 360 GeV
$\psi(2S)$ measured up to 140 GeV

Non-prompt component (from b decays) diverges from FONLL calculations for $p_T > 100$ GeV

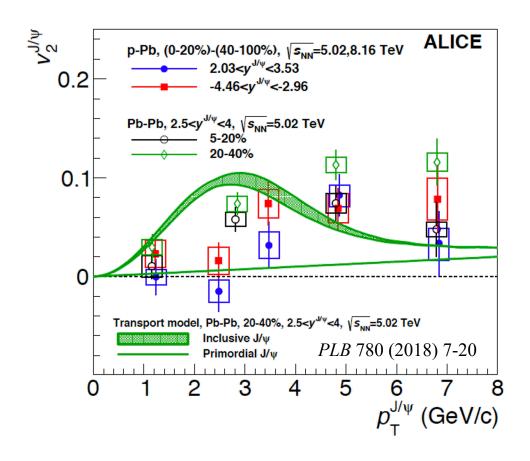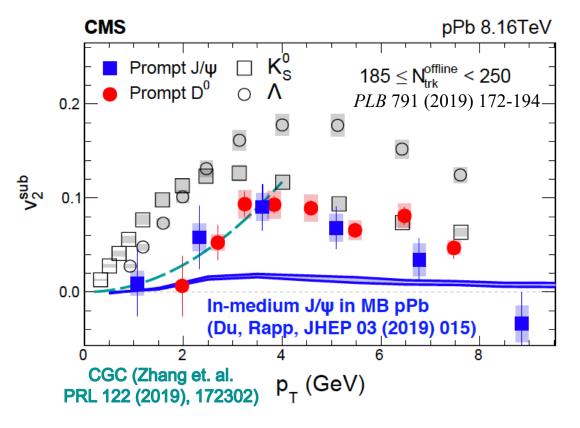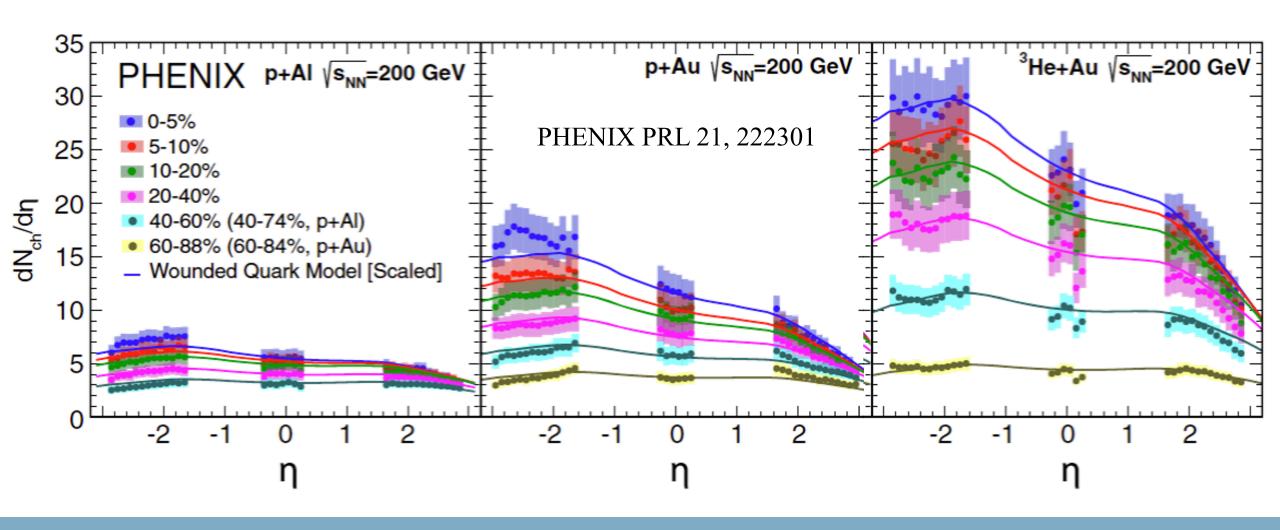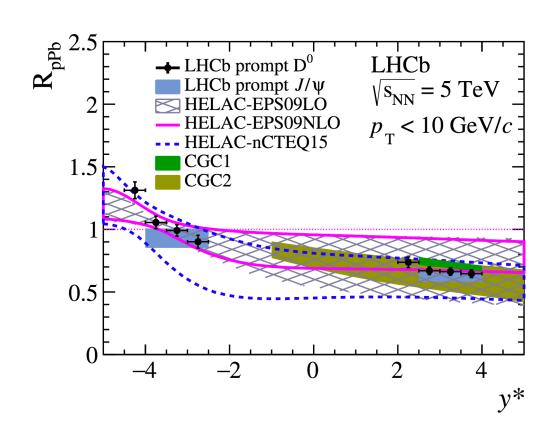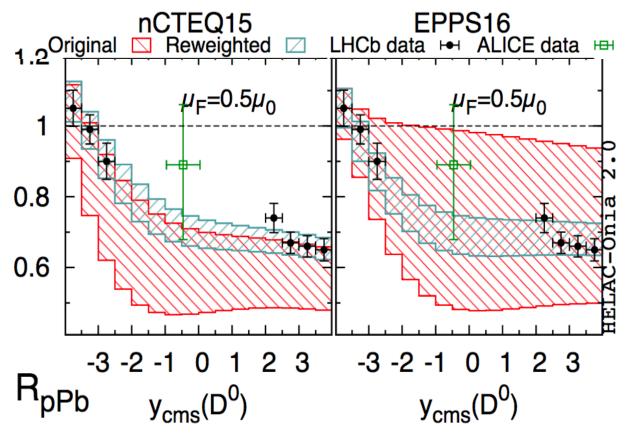# J/ψ flow: pPb and PbPb

PHENIX PRL 21, 222301
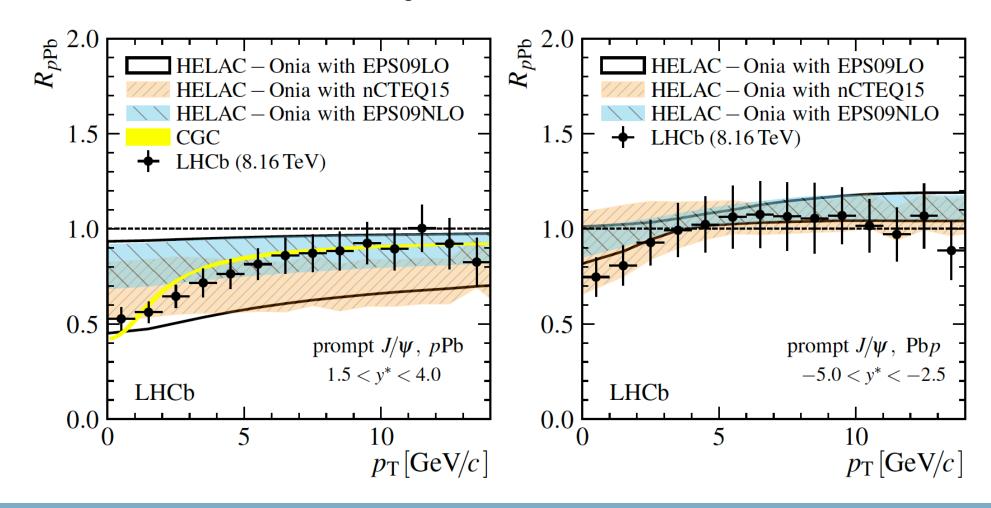
Improved nPDF extraction

This data is already being used to constrain the gluon nPDF down to x~5x10⁻⁶
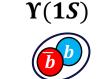
Kusina, Lansberg, Schienbein, Shao,
Gluon shadowing and antishadowing in heavy-flavor production at the LHC
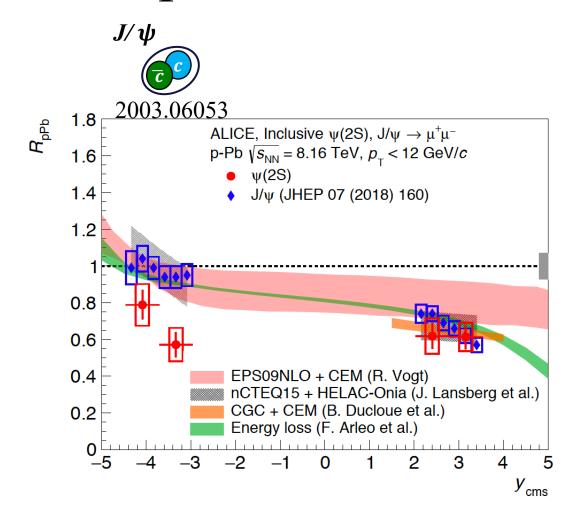**Phys. Rev. Lett. 121, 052004 (2018)**

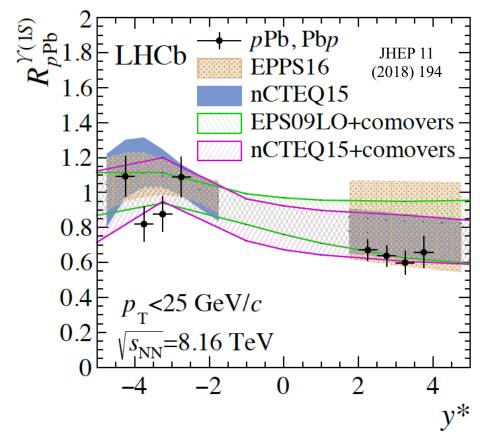Phys. Lett. B Volume 774, 10 November 2017, Pages 159-178

$Q\bar{Q}$ in pPb

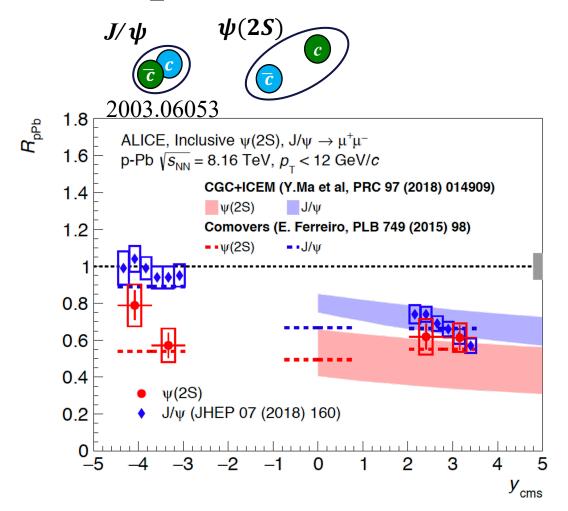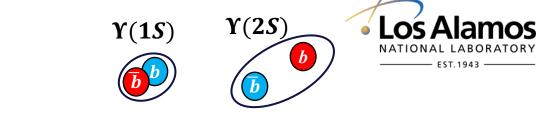At both forward and backward rapidity, J/ψ and Υ(1S) states are well described by nPDF calculations: initial state dominates
- **Marked difference from PHENIX data, where additional effects beyond nPDF were required to match backwards data**

$Q\bar{Q}$ in pPb

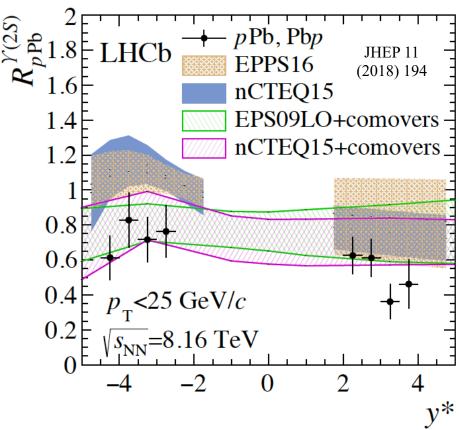

At both forward and backward rapidity, J/ψ and Υ(1S) states are well described by nPDF calculations: initial state dominates
Final state effects *required* to explain suppression of excited states at backwards rapidity

$D\overline{D}^{*}$ Molecule
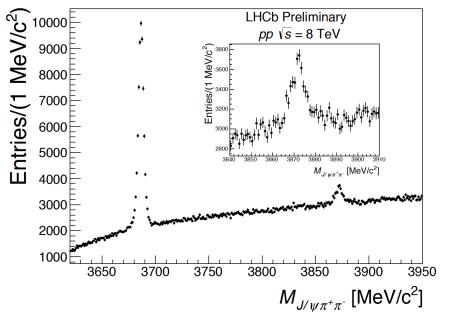
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

Satz, J. Phys. G 32 (3) 2006

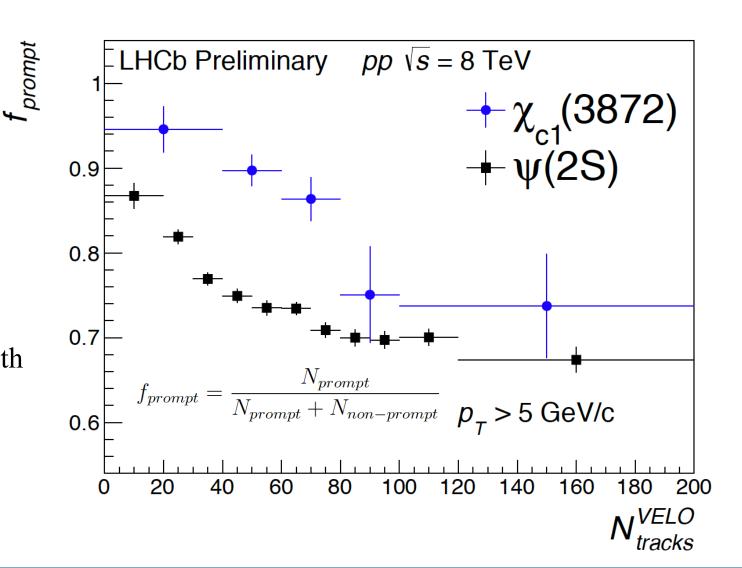# Exotic X(3872) in diffuse medium (8 TeV pp)

LHCb-CONF-2019-005

Prompt fraction of X(3872) and ψ(2S) both drop as function of event activity:
- Increasing b component?
- Suppressed prompt component?
   i.e. final state effect in pp?
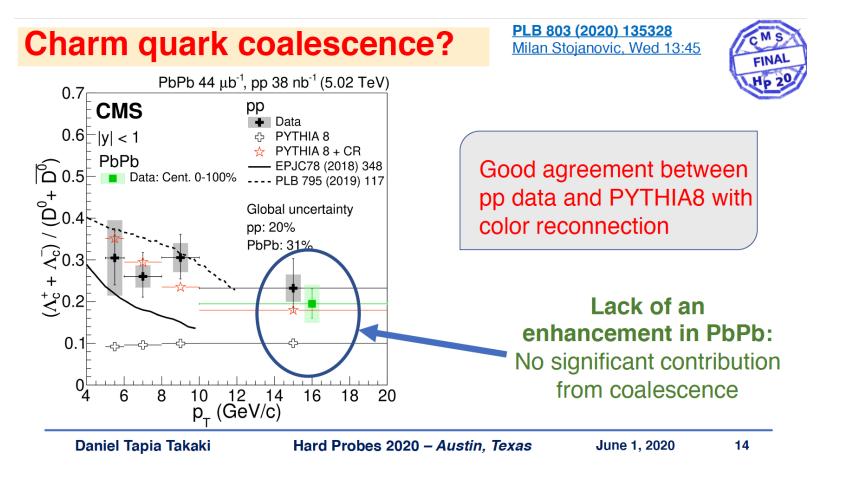
Cameron Dean, Wed 12:25

$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{non-prompt}}$$

$p_T > 5$ GeV/c

"No significant contribution from coalescence" at pT > 10 GeV/c for charm baryons

Charm quark coalescence?

PbPb 44 μb^{-1}, pp 38 nb^{-1} (5.02 TeV)

CMS
|y| < 1

PbPb
■ Data: Cent. 0-100%

pp
+ Data
PYTHIA 8
☆ PYTHIA 8 + CR
— EPJC78 (2018) 348
---- PLB 795 (2019) 117

Global uncertainty
pp: 20%
PbPb: 31%

$(\Lambda_c^+ + \Lambda_c^-) / (D^0 + \overline{D^0})$

p_T (GeV/c)

Good agreement between pp data and PYTHIA8 with color reconnection

Lack of an enhancement in PbPb:
No significant contribution from coalescence

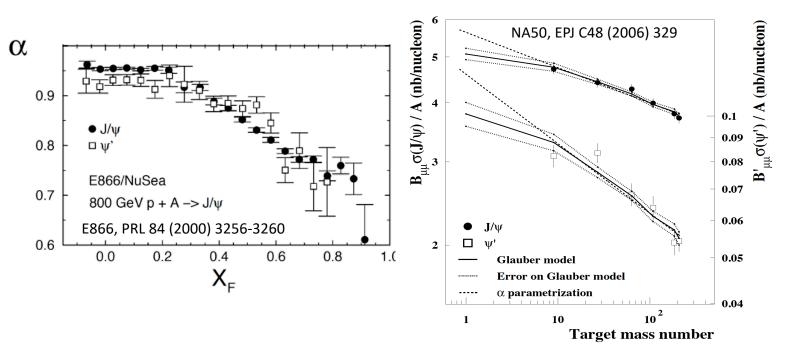**Daniel Tapia Takaki**   **Hard Probes 2020 – *Austin, Texas***   **June 1, 2020**   **14**

Quarkonia inside the nucleus

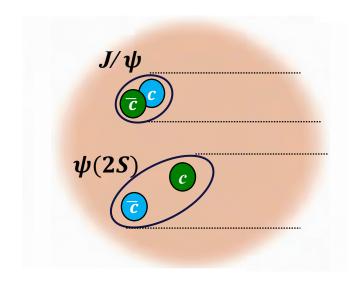Fixed target p+A experiments also operated in a kinematic region where quarkonia hadronized inside the nucleus – similar to EIC
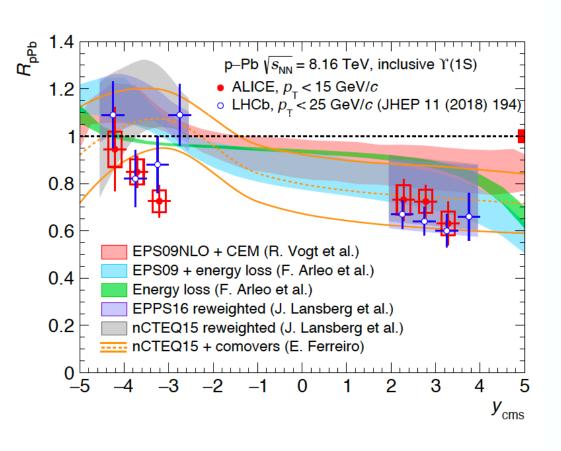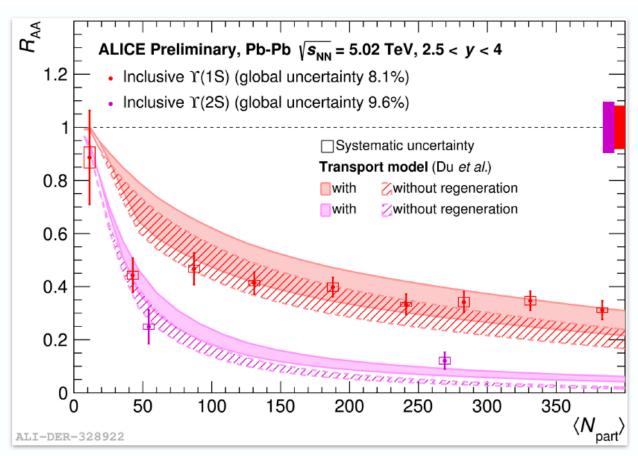

Natural explanation based on size: Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section
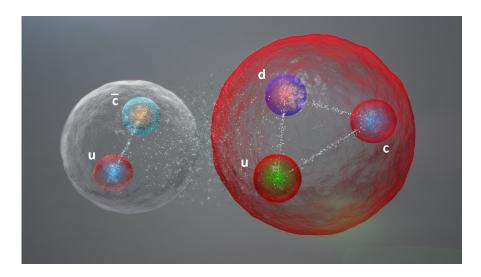
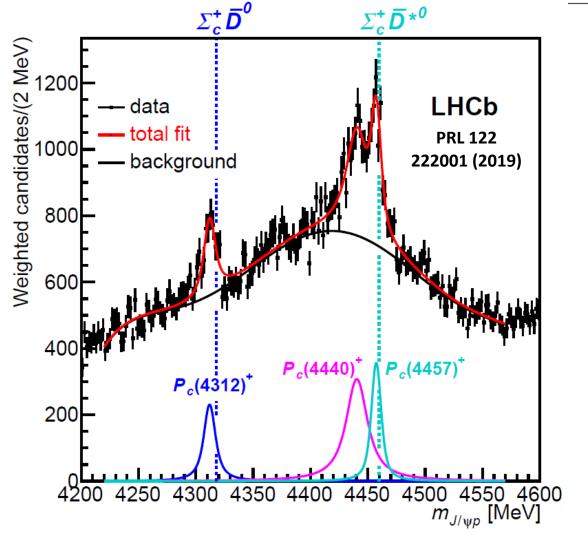Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906

Significant differences observed between states with same quark content, but different binding energies

Recent LHCb Discovery – P_c States

Select daughters from the decay

$$\Lambda_b^0 \rightarrow \boxed{J/\psi\, p}\, K^-$$

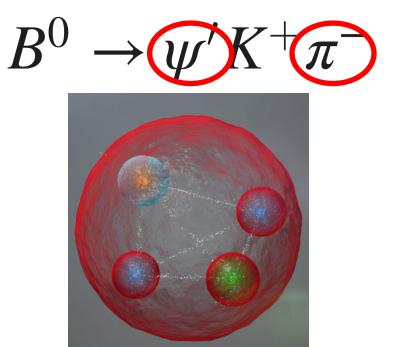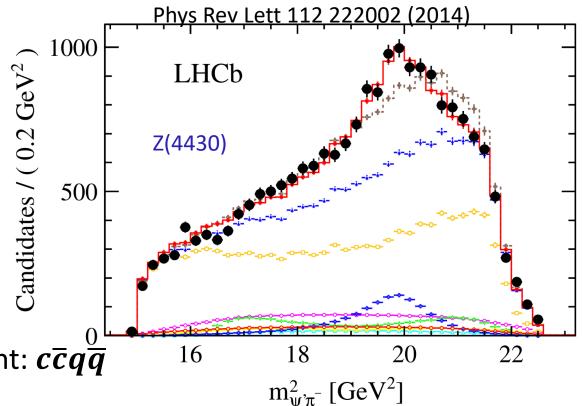**Masses are close to meson+baryon thresholds – candidate for hadronic molecule**

Charged Exotic – Z_c State

Select daughters from the decay

$$B^0 \rightarrow \psi' K^+ \pi^-$$

Phys Rev Lett 112 222002 (2014)

LHCb

Z(4430)

Candidates / (0.2 GeV^2)

$m^2_{\psi'\pi^-}$ [GeV^2]

Charged and contains $c\bar{c}$: Minimal 4 quark content: $c\bar{c}q\bar{q}$

Mass is NOT close to any hadron+hadron threshold – candidate for compact tetraquark